The possibility of detecting TeV electrons and positrons of galactic cosmic rays using the Earth's magnetic field

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Purpose

Research of the possibility of registering positrons and electrons in the TeV energy range by means of their synchrotron radiation in the Earth's magnetic field using a Monte-Carlo modeling

Topicality

The PAMELA experiment detected an anomalous effect consisting in the increase of the positron fraction in the total electron-positron flux of galactic cosmic rays at energies above ~ 10 GeV (Fig. 1)[1]. According to the AMS-02 experiment, the positron flux was determined up to the TeV region of energies [2]. These measurements confirmed the anomalous behavior of the positron spectrum at high energies. There are various hypotheses explaining the excess of positrons: annihilation and decay of dark matter, pulsars (or PWNe), supernova remnants (Fig. 2) [3-5]. To test and discriminate these hypotheses, it is necessary to measure positron flux in the TeV energy range. However, nowadays there are no effective methods for detecting high-energy positrons and electrons. In [6], O.F.Prilutsky proposed to register high-energy electrons and positrons by means of synchrotron radiation in the geomagnetic field. In our work, we modeled the characteristic of a detector based on this method.

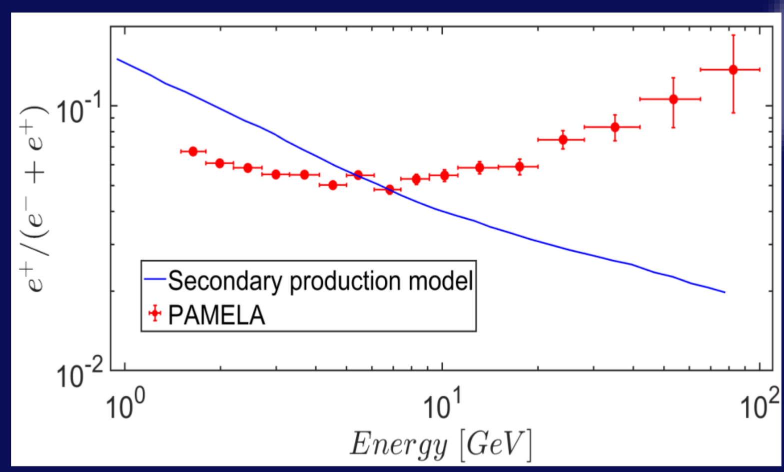


Fig. 1 The positron fraction obtained in the PAMELA experiment compared with the secondary birth model (blue solid line)

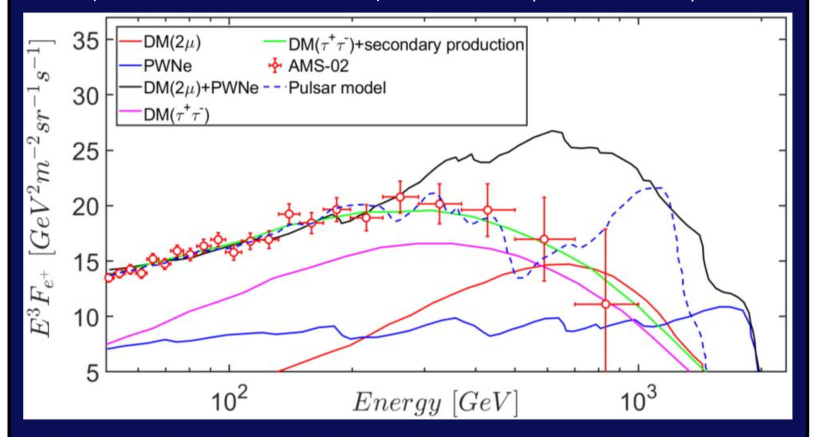


Fig. 2 Data from the AMS-02 experiment compared with different models of primary positron sources (dark matter and pulsar models).

Registration technique

A charged particle emits synchrotron radiation in the Earth's magnetic field. For light particles such as positrons and electrons, synchrotron photons are emitted in a narrow cone with an opening angle $\theta \sim \frac{mc^2}{E} \ll 1$. The detector consists of two parts: a synchrotron radiation detector (n×n pad) and electromagnetic calorimeter ECAL (Fig. 3) [7]. The positron or electron entering the calorimeter will cause a trigger signal from scintillators C1×C2 in the calorimeter. By matching the C1×C2 signals with the SRD signal within a certain time interval, it is possible to separate positrons and electrons from other particles and from each other.

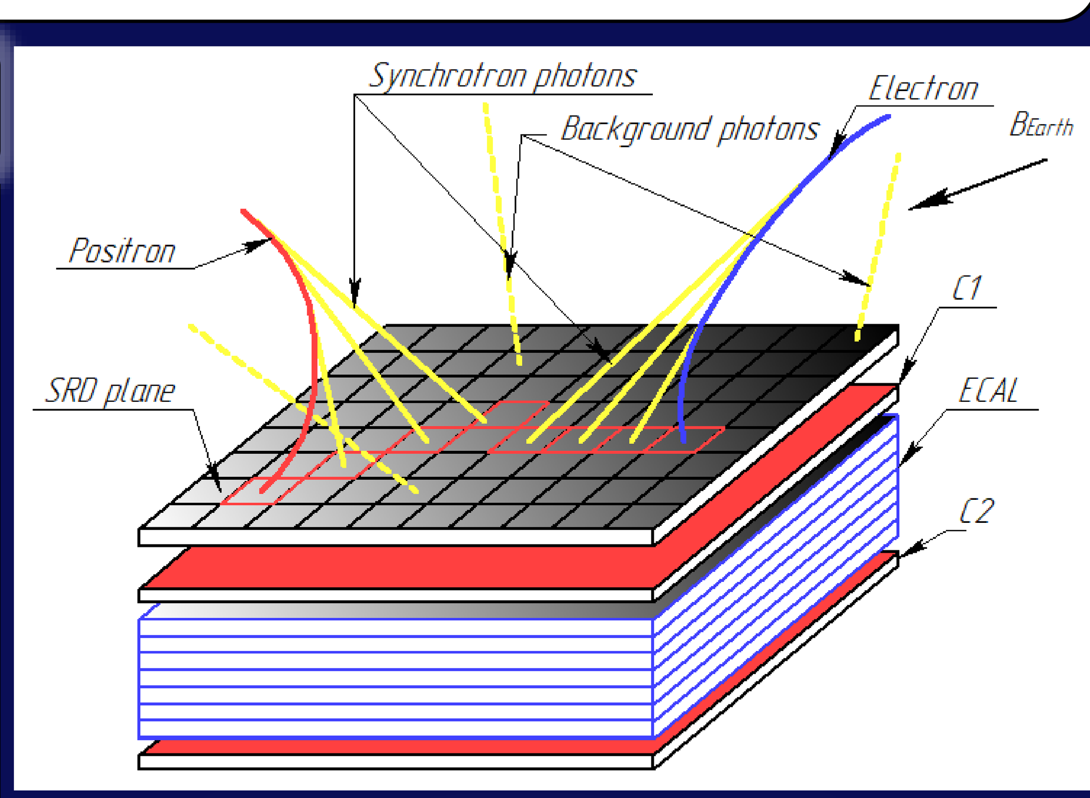
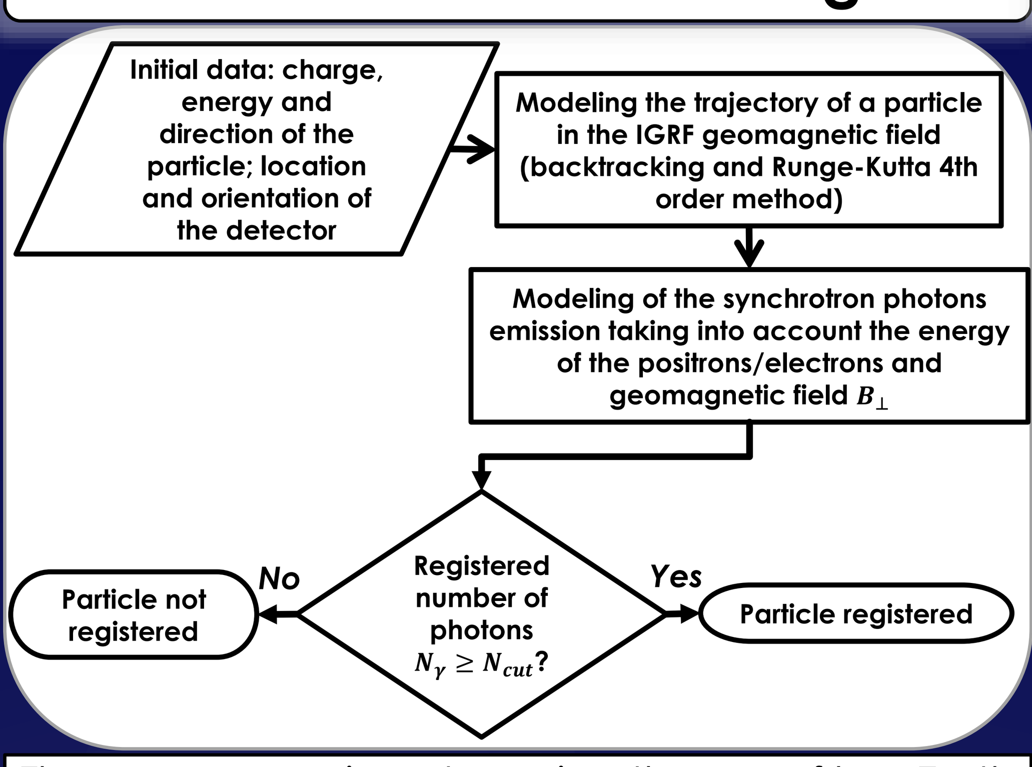


Fig. 3 Scheme for registering positrons and electrons using synchrotron radiation

e^+/e^- discrimination condition:

Registration of a positron or electron and $N_\gamma \geq 2$

Monte-Carlo modeling



The space experiment requires the use of low-Earth orbits (LEO), which provide the highest frequency of emission of synchrotron photons. In particular, the ISS orbital altitude is suitable, as well as the orbits of the planned Russian orbital service station ROSS (Fig. 4).

Modeling of photon emission

Energy spectrum

$$\frac{dN_\gamma(E_\gamma)}{dE_\gamma} = \frac{3.53 \times 10^5}{E_\gamma}\left(\frac{E_\gamma}{E_c}\right) \times \int_{E_\gamma/E_c}^{\infty} K_{5/3}(\chi)d\chi \ [8]$$

$$E_c = 6.56 \times 10^{-2} B_\perp E_0^2 \ [MeV]$$

Photon emission probability

$$l = \frac{1.6 \times 10^5 \ cm}{H(Gauss)} [6]$$

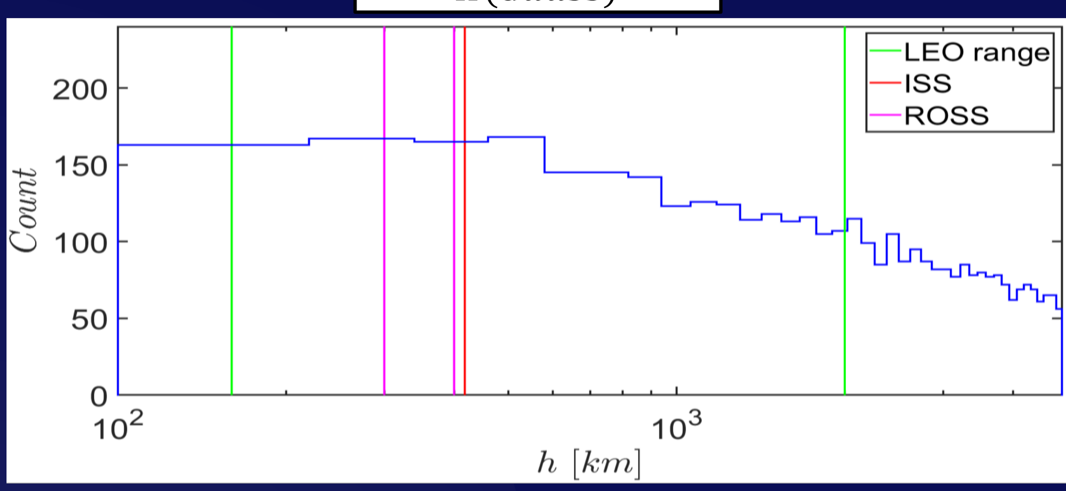


Fig. 4 High-altitude distribution of synchrotron photons from a positron with an energy of 5 TeV. The altitude ranges of LEO and the orbits of the planned ROSS are shown by the green and magenta lines

Useful events selection technique

The registration point (x_0,y_0) of the e^+/e^- is determined by the C1×C2

1. Forming a scanning strip of parallel lines from the point (x_0,y_0) at distance d;
2. With a small step $\Delta\alpha \leq 1°$, the strip rotates with respect to the point (x_0,y_0) and counts the number of photon events caught in its area;
3. Angle $\alpha_{max(N)}$ of the strip with the maximum number of hit events is recorded.

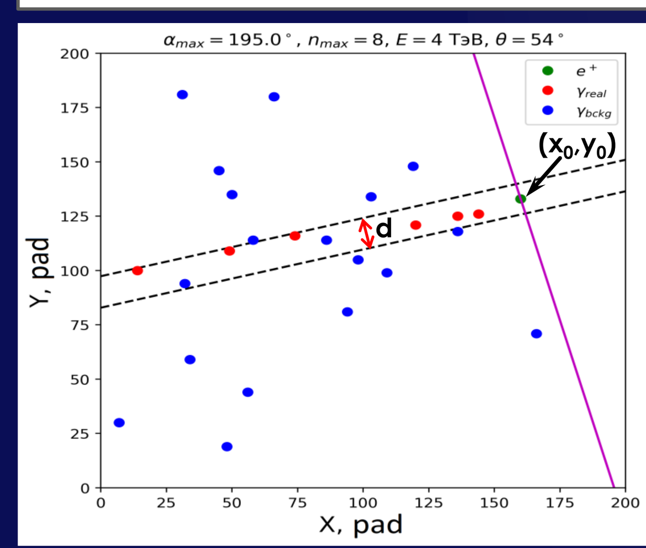


Fig. 5 Model of event separation

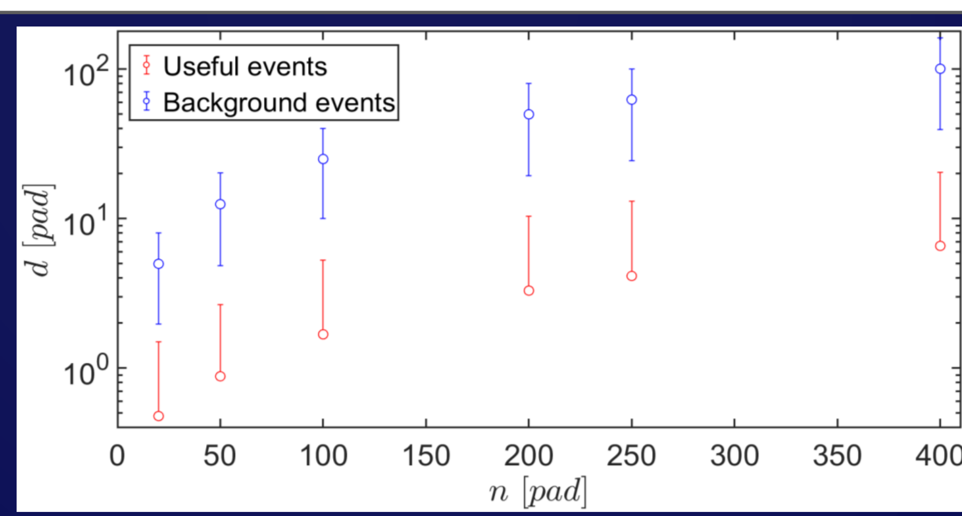


Fig. 6 Dependence of the average photon dispersion d in pad relative to the straight line on the number of n × n pad in the matrix structure of the detector plane. The errors show two standard deviations

Results

e^+/e^- discrimination

Two ways of determining the ratio of electrons to positrons are considered: by the distribution of photons from a set of events and by analyzing the tracks found for each event.

Figure 7 shows the distribution of synchrotron photons in the 2 × 2 m detector plane from electrons and from positrons at the equator. Analysis of such distributions may allow to determine the ratio of electrons to positrons by the density of synchrotron photon distribution in a particular region of the detector.

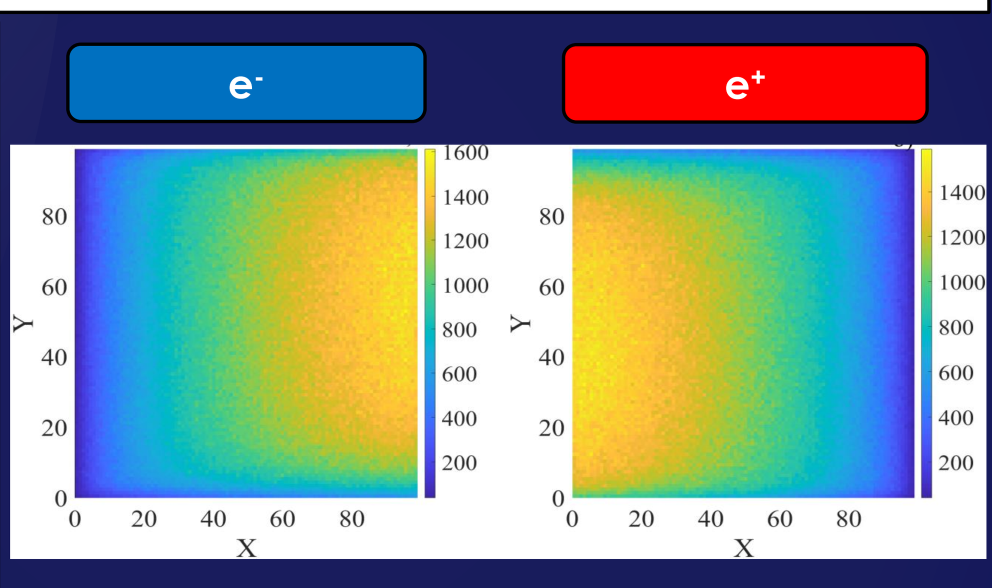


Fig. 7 Photon distributions in the 100 × 100 pixel detector plane at the equator from electrons and positrons

Identification of the particle track for each event using the described technique of useful event selection also makes it possible to determine the charge sign. Figure 10 shows the probabilities η_z of the charge sign error as a function of energies for different average background $< N_{bckg} >$.

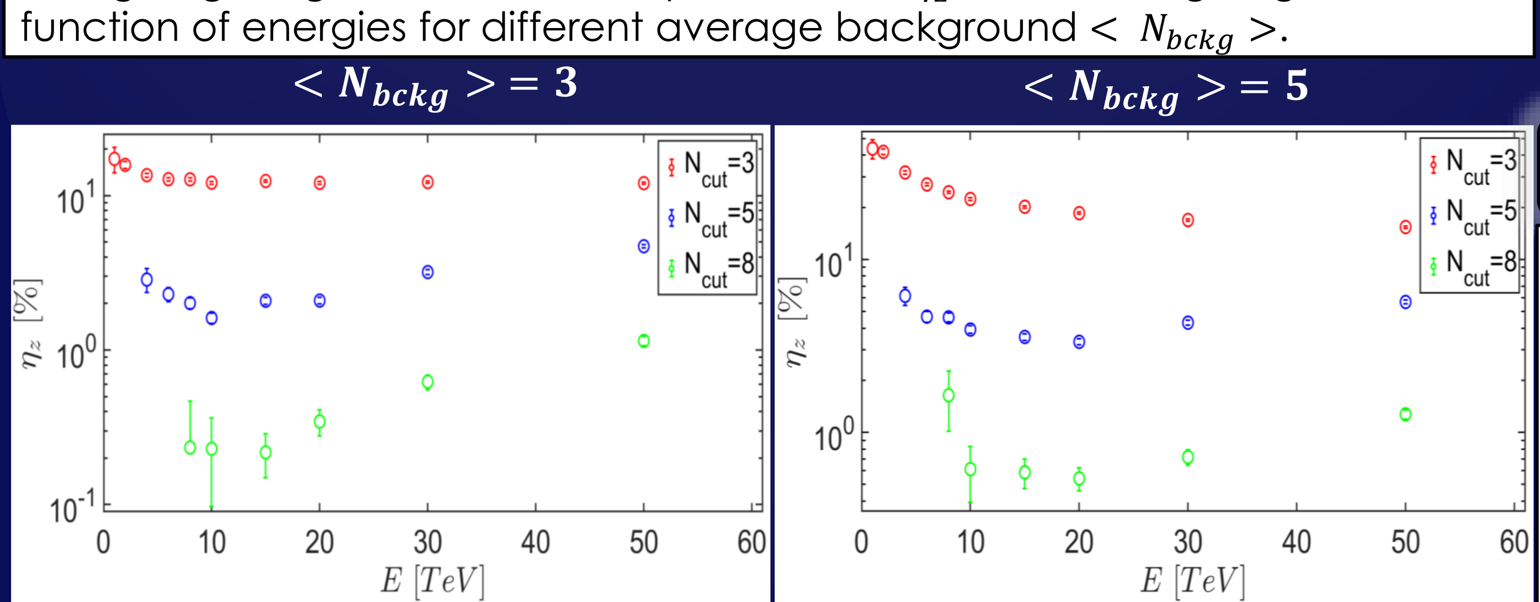


Fig. 10 The dependence of the probability η_z of the error in determining the sign of the charge on the energy of the particle. 200 × 200 pad detector

Indirect energy determination

Figure 8 shows the calibration dependences of the average energy of synchrotron photons on the energy of positrons. The calibration was performed for a constant lower photon registration threshold of 1 keV. The upper registration threshold ranged from 200 keV to 100 MeV.

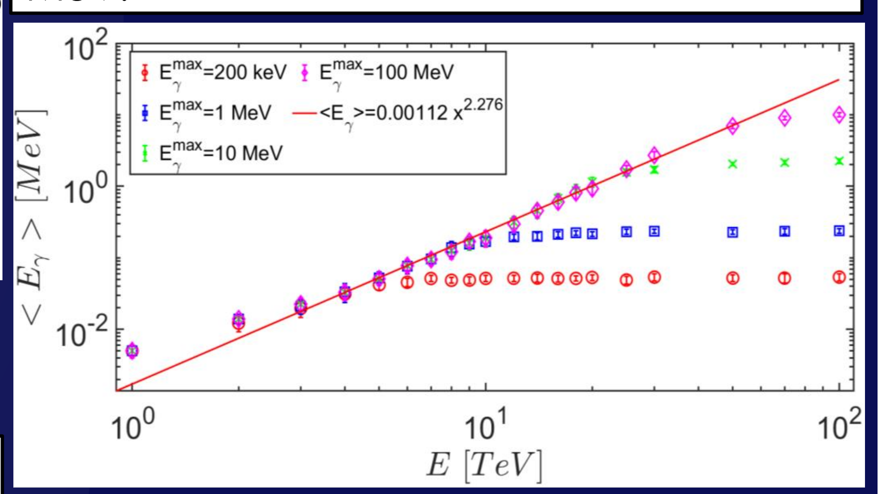


Fig. 8 Calibration dependences of the average energy of synchrotron photons energy of positrons at different energy ranges of synchrotron radiation. Registration of at least N_{cut} = 3 photons. ISS orbit.

Count rate

The expected integral annual count rate is calculated for the orbits of ISS and ROSS orbits with inclinations 51.6° и 96° respectively at an altitude of 400 km above the Earth. To simulate the detector locations on circular orbits, we averaged over the stationary positions on them in 30° increments. The results are shown in Figure 9. To determine the geometric factor of the detector with rectangular geometry, we used formulas from [9].

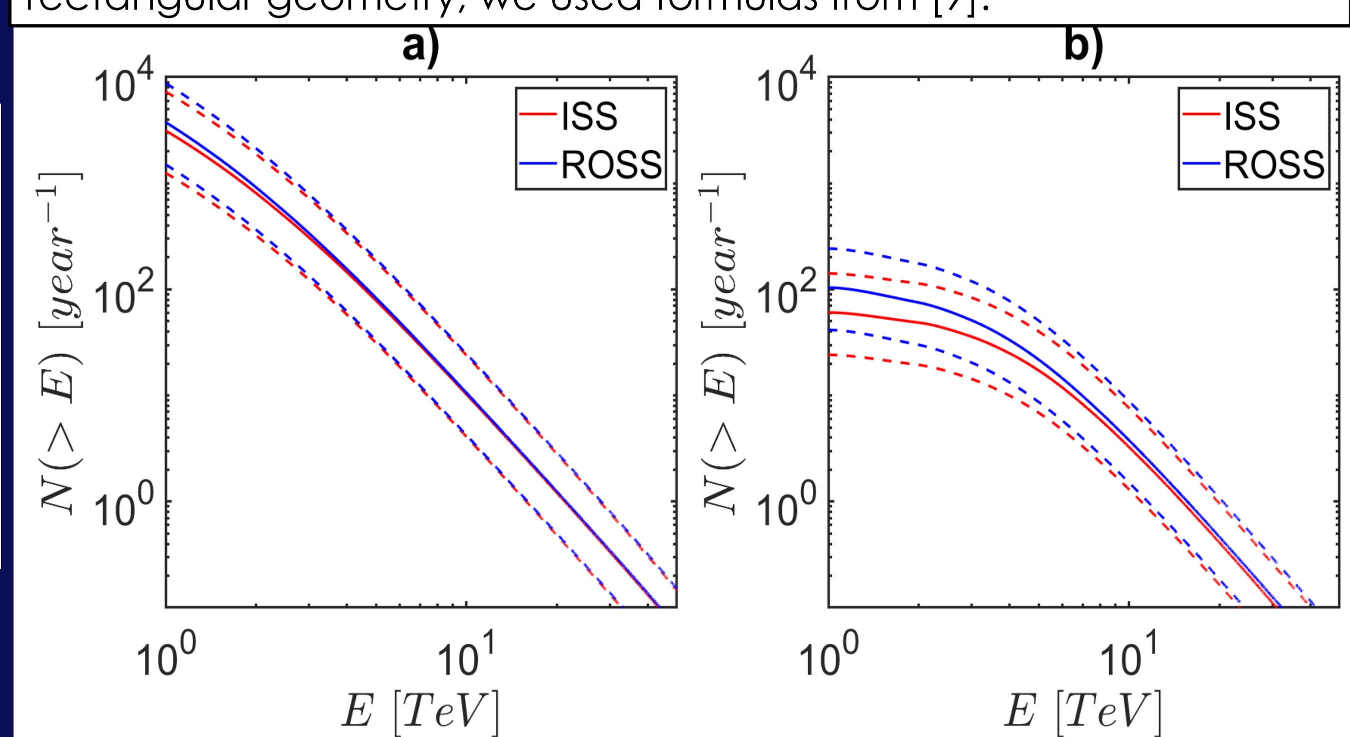


Fig. 9 Energy dependence of the expected integral annual rate of the 200 × 200 pad detector count. N_{cut} = 2 (a) and N_{cut} = 5 (b). Geometric factor $10 \ m^2 sr$. Photon detection range is 1 keV to 1 MeV. The error areas are shown by the dotted lines of the corresponding colors

Conclusion

In this work we studied the possibility of registering positrons and electrons of TeV energies by means of synchrotron radiation in the magnetic field of the Earth.
A technique for separating tracks of useful events from background events is developed and applied. The technique is applied for the discrimination of electrons and positrons. The probabilities of incorrectly determining the sign of the charge are obtained. For a particular event it is ≤ 2 % for the N_{cut} = 5 and ≤ 1 % for N_{cut} = 8 with an average background level $< N_{bckg} >$ = 3. The possibility of determining the ratio of electrons to positrons by their synchrotron photon distribution density in the detector plane is also demonstrated.
Based on data from the CALET, DAMPE, and FERMI experiments, the expected count rate of the detector is estimated . It is shown that the orbit of the planned ROSS provides a better measurement statistic.

References

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